

Characterization of Deficiencies in the Frequency Domain Forced Response Analysis Technique for Supersonic Turbine Bladed Disks

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Turbine blades in rocket and jet engine turbomachinery experience enormous harmonic loading conditions. These loads result from the integer number of upstream and downstream stator vanes as well as the other turbine stages. Assessing the blade structural integrity is a complex task requiring an initial characterization of whether resonance is possible and then performing a forced response analysis if that condition is met. The standard technique for forced response analysis in rocket engine turbines is to decompose a computational fluid dynamics (CFD)–generated flow field into its harmonic components, and to then perform a frequency response analysis at the problematic natural frequencies using cyclically symmetric structural dynamic models. Recent CFD analysis and water-flow testing at NASA/MSFC, though, indicates that this technique may miss substantial harmonic and non-harmonic excitation sources that become present in complex flows. This complex content can only be captured by a CFD flow field encompassing at least an entire revolution. A substantial development effort to create a series of software programs to enable application of the 360° forcing function in a frequency response analysis on cyclic symmetric models has been completed (to be described in a future paper), but the question still remains whether the frequency response analysis itself is capable of capturing the excitation content sufficiently.

Two studies comparing frequency response analysis with transient response analysis, therefore, of bladed-disks undergoing this complex flow environment have been performed. The first is of a bladed disk with each blade modeled by simple beam elements and the disk modeled with plates (using the finite element code MSC/NASTRAN). The focus of this model is to be representative of response of realistic bladed disks, and so the dimensions are roughly equivalent to the new J2X rocket engine 1st stage fuel pump turbine. The simplicity of the model allows the CFD load to be able to be readily applied, along with analytical and experimental variations in both the temporal and spatial fourier components of the excitation. In addition, this model is a first step in identifying response differences between transient and frequency forced response analysis techniques. The second phase assesses this difference for a much more realistic solid model of a bladed-disk in order to evaluate the effect of the spatial variation in loading on blade dominated modes. Neither research on the accuracy of the frequency response method when used in this context or a comprehensive study of the effect of test-observed variation on blade forced response have been found in the literature, so this research is a new contribution to practical structural dynamic analysis of gas turbines.

The primary excitation of the upstream nozzles interacts with the blades on fuel pump of the J2X causes the 5th Nodal diameter modes to be excited, as explained by Tyler and Sofrin¹, so a modal analysis was first performed on the beam/plate model and the 5ND bladed-disk mode at 40167 hz was identified and chosen to be the one excited at resonance (see figure 1). The first forced response

analysis with this model focuses on identifying differences between frequency and transient response analyses. A hypothesis going into the analysis was that perhaps the frequency response was enforcing a temporal periodicity that did not really exist, and so therefore it would overestimate the response. As high dynamic response was a considerable source of stress in the J2X, examining this concept could potentially be beneficial for the program.

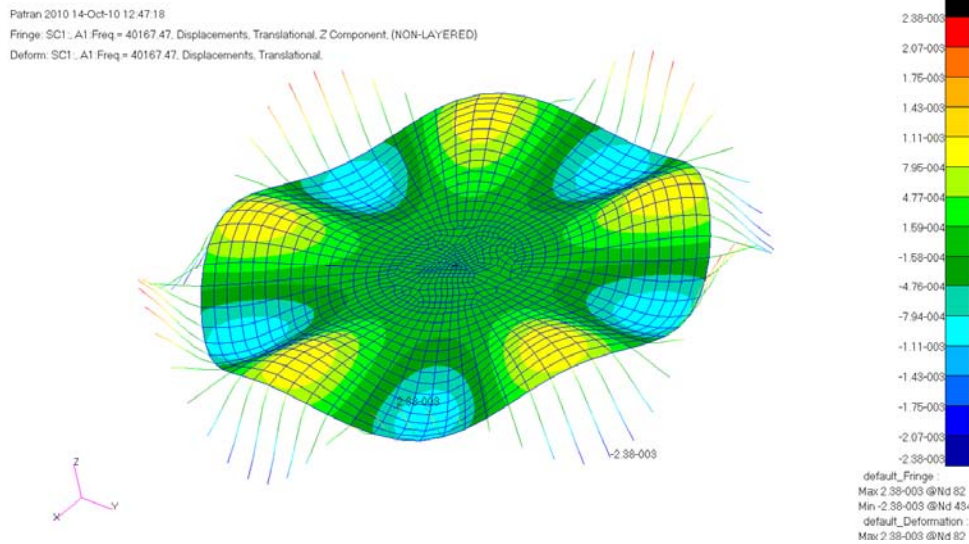


Figure 1 Beam/Plate bladed disk model, 5ND mode at 40167hz

To perform the frequency response analysis, the 4 revolution (of the disk) CFD analysis performed for the real turbine was scaled such that the applicable primary excitation temporal Fourier component $F_0 e^{i\Omega t}$ has a frequency equal to the mode of interest, and the complex loading (real and imaginary components) of the component is applied in the frequency response NASTRAN solution. This analysis is very quick because it uses the modal transformation

$$\{u\} = [\Phi] \{q\}$$

to decompose the very large model into modal components $\{q\}$. The response can then be calculated by superimposing the modal single-frequency responses each calculated using the standard complex single degree of freedom frequency response equation

$$q(t) = \bar{H}(\Omega) \bar{U}_{static} = \left[\frac{1 - \Omega/\omega_t^2}{(1 - \Omega/\omega_t^2)^2 + \zeta^2} + i \frac{-2\zeta\Omega/\omega_t^2}{(1 - \Omega/\omega_t^2)^2 + \zeta^2} \right] \frac{F_0 e^{i\Omega t}}{\omega_t^2}$$

The peak values of the response for the highest responding nodes are shown in figure 2.

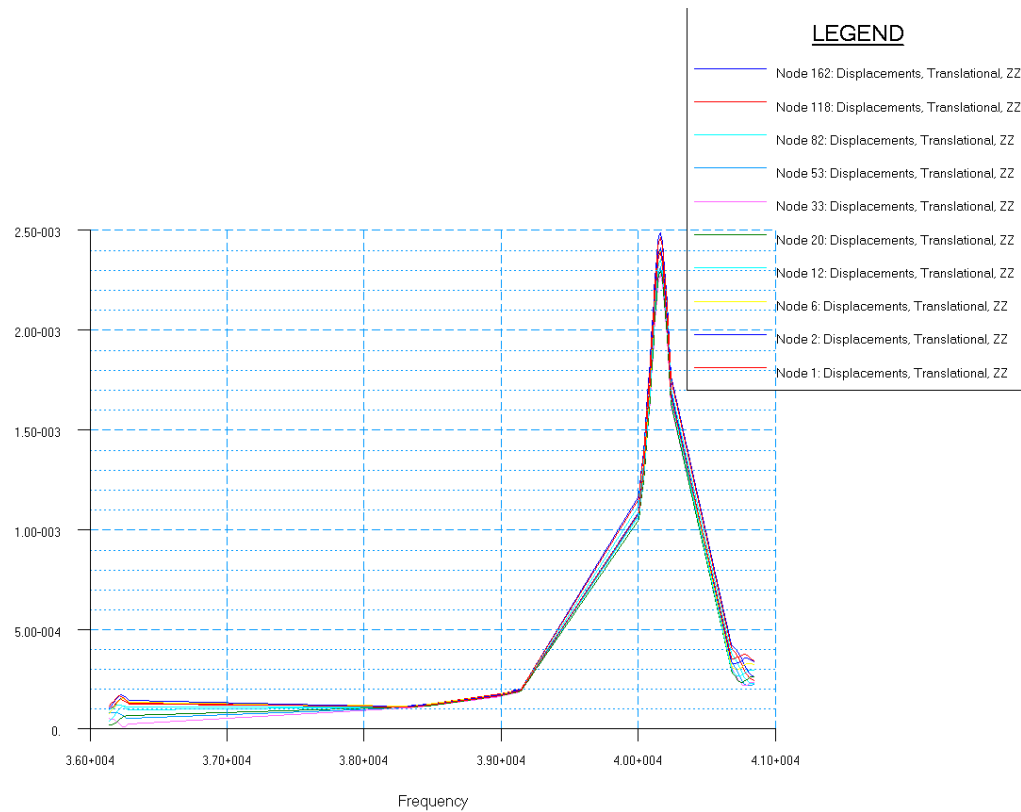


Figure 2 Peak Frequency Response of Highest Responding Nodes in Beam/Plate model

A transient analysis was then performed. In this context, this type of analysis refers to calculating the response to the complete excitation function in the temporal domain. As this type of analysis typically uses a time marching scheme, it is significantly more computer CPU-intensive than frequency response analyses, and so in general is not tractable for realistic high-fidelity solid finite element models of bladed-disks. The main difficulty for this model was creating the NASTRAN format for different high-resolution time histories on each of the blades. Interpreting the results is also trickier than for the frequency response method, as the static load component of the load is not removed. These issues require plotting of the entire time history of the tip node response for a 1/5 sector of the bladed-disk (corresponding to the 5ND mode shape), zooming in on portions appearing to have the highest response, and measuring peak-to-peak amplitudes. These amplitudes are then divided by two for comparison to frequency response results. The results are shown in figure 3.

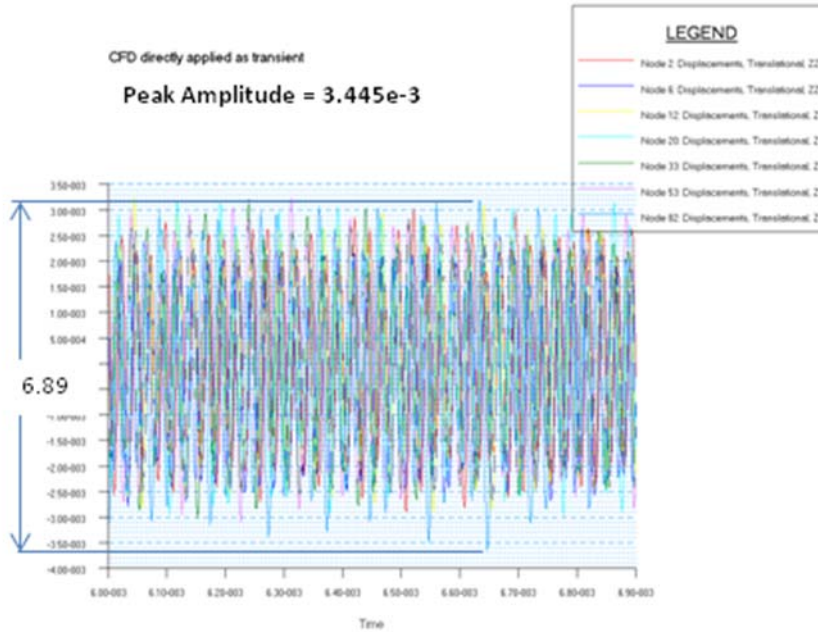


Figure 3 Peak Transient Analysis Response of Highest Responding Nodes in Beam/Plate Model

The comparison was somewhat unexpected. Rather than overestimate the response, the peak frequency response was 43% less than the peak transient results. The most probable cause for the difference was thought to be contributions from frequency components of the excitation close to the fundamental excitation, which is all that is used in the frequency response analysis. These effects were investigated by taking those nearby components, as shown in figure 4, and performing frequency response analyses using those amplitudes at those slight off-resonant frequencies. When summed together, the responses of these “sidebands” do appear to have enough energy to equal the transient; however, the phasing of the sidebands is such that their peaks would line up with the fundamental peak so rarely that the likelihood of the combined effect making up the 43% difference is unlikely. The investigation of this issue is continuing and will be discussed in more detail in the final paper.

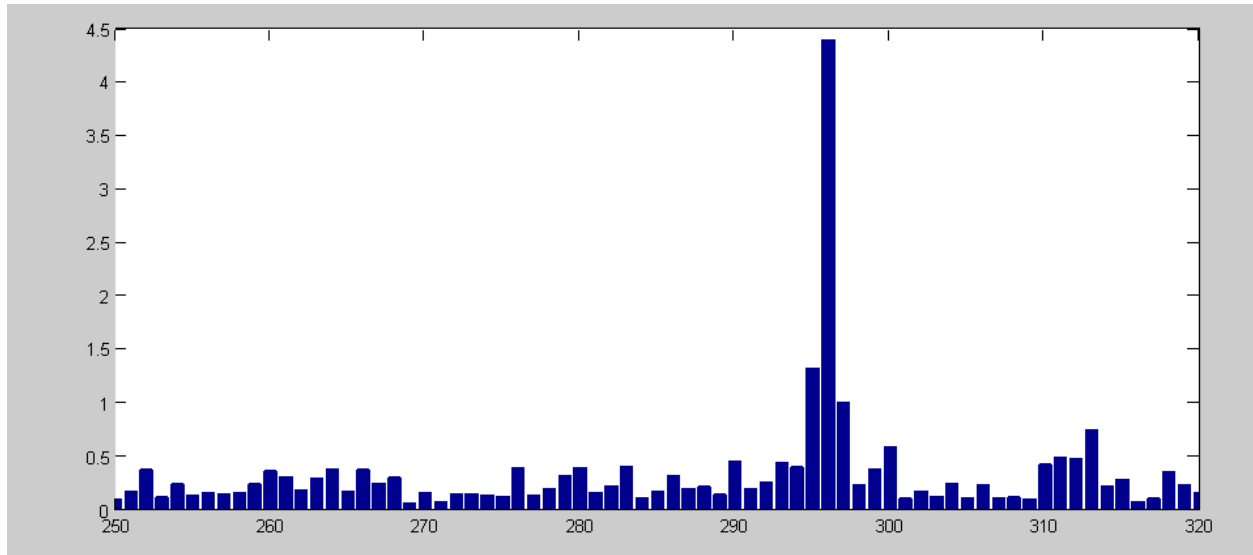


Figure 4 – Magnitude of loading from sidebands of fundamental excitation in bin 296.

The next phase of the study was to assess the affect of temporal and spatial variations in the loading as measured in cold-flow testing from the Heritage Fuel Air Turbine Test conducted at MSFC in 2010. It was hypothesized that the randomness and other variations from the standard harmonic excitation would reduce the blade structural response. Six loading cases were generated by varying a baseline CFD harmonic excitation in different ways based upon the test as shown below:

$$[\overline{A} + A(t)]\cos \left\{ \omega t + k\theta + [\overline{\phi} + \phi(t)] \right\}$$

where the time varying amplitude and phase terms $A(t)$ and $\Phi(t)$ are based on the test observations. The analyses were performed in the time domain to be able to include these variations. The results showed no change in the peak values when including the time varying phase only, an 8% increase when including only the varying amplitude, but a substantial increase of 25% when both terms are included. The full paper will include a statistical analysis of the peak responses and further discussion of these results.

The final phase of the research program was motivated by the question of what the effect of slightly aperiodic excitation would be on blade-dominated modes, rather than the nodal diameter dominated modes of the beam/plate model. This required the construction of a solid element bladed-disk model with a representative airfoil. As before, a 360° model was built to be able to readily load it with the same 360° CFD loading as used in the J2X engine program. The model was quite large, as shown in figure 5, but was made manageable by using the new glued-contact formulation in MD-Nastran, which enables a much simpler model of the disk than of the blades by allowing dissimilar meshes at the interface. Once again, for this case, it was hypothesized that the frequency response would overestimate the transient because the requirement that the spatial distribution of the loading

on each blade matches the mode shape would be made artificially periodic. A modal analysis was first performed and the 5ND mode at 40264 hz was identified for resonant excitation. In addition, since 12ND content is also found in the fluid forcing function, a 12ND mode at 40883 hz was identified for analysis. Frequency and transient analysis were then performed, and even with the mesh-reduction, the transient analysis was still tremendously CPU-intensive as a temporal loading for each of 29,000 grids on the blades was applied to the model. As with the beam/plate model, the results showed that while the averages for the two types of analysis were approximately equal, the transient analysis peak results exceeded the frequency response; they were up to 10% higher for “clean” nodal diameter excitations like the 5ND and six times larger for “messy” excitations like the 12ND, where substantial Fourier content around the main harmonic exists.

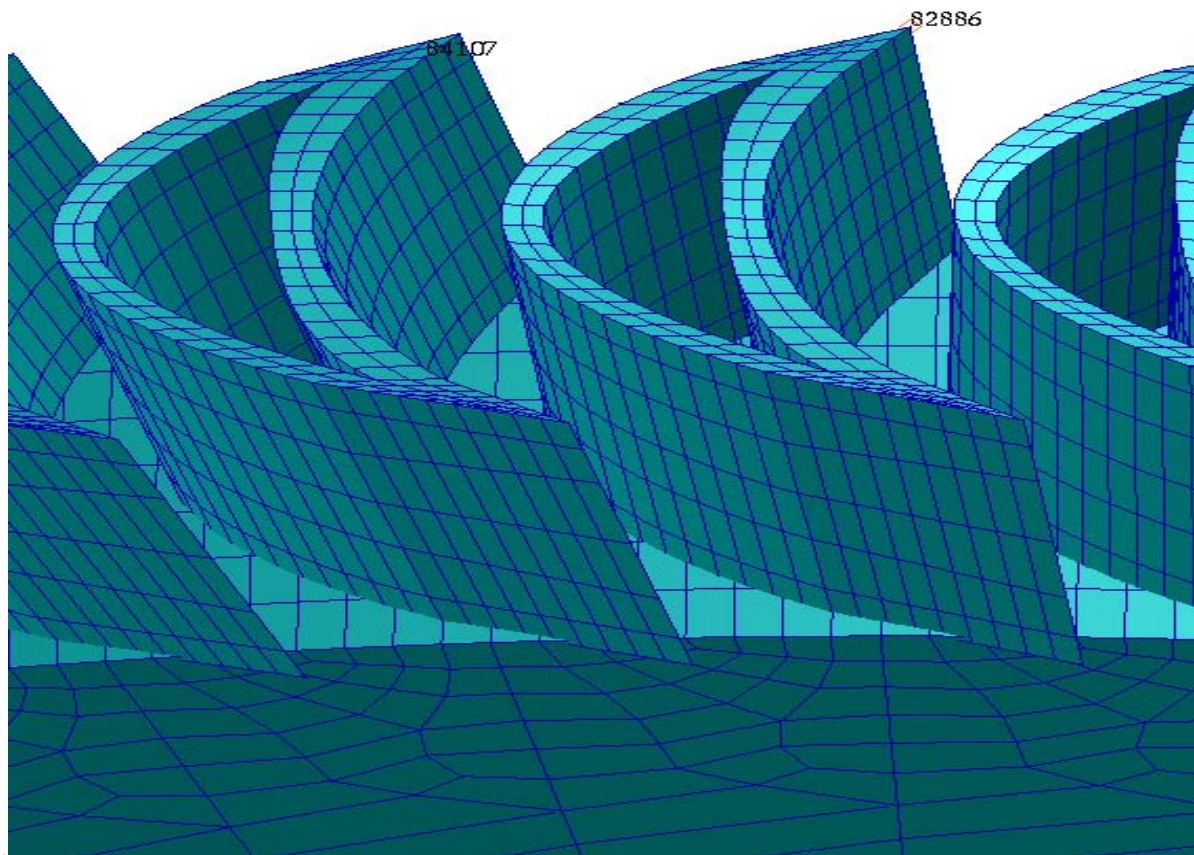


Figure 5 – Solid Element Representative Bladed-Disk Model (not to scale)

Because the bulk of fatigue damage occurs at levels equal to and above 2σ of the distribution of the peaks, therefore, the higher peaks would probably cause more damage. Statistical analysis of these peaks is therefore being performed for a true comparison. In addition, in the rare cases when the “messy” excitations harmonics are identified as the source of potential resonance concerns, this research does indicate that frequency response analysis could be substantially inadequate for accurate

characterization of blade structural capability. The overall effect of the differences between transient and frequency response analysis for this application are still being quantified and their implications will be further discussed in the final paper.

¹ Tyler, J.M., Sofrin, T.G., Axial Flow Compressor Noise Studies, 1961